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Looking for hysteresis in coal consumption in the US

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ABSTRACT

This paper estimates an unobserved components model to explore coal consumption in the USA. We ask whether coal consumption exhibits *hysteresis*, defined as a dynamic structure in which the cyclical component of coal consumption has permanent effects on the natural component. In contrast to previous analysis, we provide evidence in favor of hysteresis in coal consumption, by using the nonlinear framework proposed recently by Pérez-Alonso and Di Sanzo [13], in which threshold type nonlinearities are introduced by allowing past cyclical consumption to have a different impact on the natural component depending on the regime. The article discusses implications of the findings for energy conservation policies.

Contents

1. Introduction

Efforts to find alternative and cleaner energy sources are intensifying given the public interest in the reduction of the negative effects of carbon dioxide emissions. But meanwhile governments around the world regard energy conservation policies as a promising candidate in this respect. In this context, the study of the effects of these conservation policies on the reduction of energy consumption is a highly hot topical issue at the time of writing, given that these interventions often impose sizeable costs on the taxpayer.

Given these costs, the lack of robust evidence associating these policies with long term effects on the consumption is particularly striking.[1] At the heart of this question is how energy consumption evolves. If energy consumption is trend-stationary, policy shocks such us the energy conservation policy can be regarded as transitory: energy consumption eventually reverts to its underlying, long-run ("natural") component. For instance, one can conceive of an energy conservation policy, which thereby creates a downward shift in consumption. If energy consumption is stationary, the shock dies away once the policy has been implemented, and energy consumption settles up at its new, lower, level. If on the other hand the energy consumption is non-stationary, such shocks can have permanent effects. For example, the energy conservation

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[1] The available evidence is mixed. Some authors suggests that energy consumption is stationary in which case policies oriented toward the reduction of energy consumption only have short-term effects [4–7] while others [8,9] provides evidence on the contrary.

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policy considered above, decreases energy consumption in a way which affects all subsequent levels of consumption. A necessary (but not sufficient) condition for this to occur is a unit root in energy consumption.

In a time-series context, hysteresis can be defined and measured in various ways. A popular approach in the empirical literature simply equates hysteresis with the existence of a unit root in a variable (see, Røed [1], for a survey). An alternative approach proposed by Jaeger and Parkinson [2,3] posits a more demanding criterion: hysteresis exists if shocks (such as the one-off policy change discussed above) affect the natural component of a variable, which itself follows a unit root process. In which case, temporary shocks have permanent effects while the cycle does not evolve independently of the natural component; it then follows that a unit root is a necessary but not a sufficient condition for hysteresis. In this article, we adopt Jaeger and Parkinson's [2,3] definition of hysteresis in order to conduct a searching test and to explore whether energy conservation policies on coal consumption have long-term effects.

To test for hysteresis in this way, we decompose coal consumption into two unobservable components: a non-stationary "natural or permanent" component, and a stationary "cyclical" component. These components can be estimated by maximum likelihood using the Kalman filter. Although Jaeger and Parkinson's approach has been applied extensively in labor economics [10–13] to the best of our knowledge its application to energy economics is novel.

Once hysteresis is tested in the linear model, the new test for hysteresis based on a nonlinear unobserved components model, proposed by Pérez-Alonso and Di Sanzo [13], is applied. This test introduce, threshold type nonlinearities by allowing past cyclical component to have a different impact on the natural component depending on the regime of the economy. Note that we must take into account this possibility because the estimation of linear relations could yield spurious inference results if the nonlinear model provides a better empirical description of our data.

A further motivation for our empirical analysis is that hysteresis exists this implies that energy conservation policies might be more powerful than has been thought hitherto.

This article has the following structure. The next section describes the data and the estimation methodology. The third section presents and discusses the results. The final section concludes with a discussion of policy implications and some promising avenues for future research.

2. Data and methodology

2.1. Data

The data used are quarterly observations from 1973:1 to 2010:3. The coal consumption (measured in thousand short tons) and GDP data (measured in billions of chained 2005 dollars) are extracted from the U.S. Energy Information Administration (EIA) and the U.S. Bureau of Economic Analysis (BEA), respectively. Before conducting the empirical analysis data were seasonally adjusted.

2.2. Econometric methodology

As we mentioned before, several empirical studies equate hysteresis in a time series with a unit root process. Others argue that hysteresis arises when changes to the cyclical component of a time series, C_t^C, induce permanent changes in the "natural" component of the series, C_t^N. This is different to a unit root process. To comprehend the different estimation strategies these approaches call for, decompose the series C_t into the sum of its two (unobservable) components: the non-stationary natural component, C_t^N, and the stationary cyclical component, C_t^C:

$$C_t = C_t^N + C_t^C \tag{1}$$

Now define the natural component as a random walk plus a term capturing a possible hysteresis effect:

$$C_t^N = C_{t-1}^N + \beta C_{t-1}^C + \varepsilon_t^N \tag{2}$$

where the β coefficient measures, in percentage points, how much the natural component increases if the consumption experiences a cyclical increase of 1%. Evidently a unit root in the consumption C_t is necessary but not sufficient condition for the existence of hysteresis since a unit root could be generated by an accumulation of shocks to the natural component C_t^N while at the same time $\beta = 0$ [1]. In contrast, there is hysteresis if $\beta > 0$.

The specification of the model is completed by writing the cyclical component as a stationary second-order autoregressive process[2]:

$$C_t^C = \varphi_1 C_{t-1}^C + \varphi_2 C_{t-2}^C + \varepsilon_t^C \tag{3}$$

where φ_1 and φ_2 provide a measure of the periodicity of the cyclical component.

To identify the model, the system is completed by augmenting it with an equation, which relates the cyclical component of the coal consumption and output growth,

$$D_t = \alpha D_{t-1} + \delta C_t^C + \varepsilon_t^D \tag{4}$$

where D_t stands for the output growth rate at date t.[3]

The random shocks ε_t^N, ε_t^C and ε_t^D are assumed to be mean-zero draws from the normal distribution with variance–covariance matrix Ω; the state-space form of the model can be written as

$$C_t = \begin{pmatrix} 1 & 1 & 0 \\ 0 & \delta & 0 \end{pmatrix} \begin{pmatrix} C_t^N \\ C_t^C \\ C_{t-1}^C \end{pmatrix} + \begin{pmatrix} 0 \\ \alpha \end{pmatrix} D_{t-1} + \begin{pmatrix} 0 \\ \varepsilon_t^D \end{pmatrix} \tag{5}$$

$$\begin{pmatrix} C_t^N \\ C_t^C \\ C_{t-1}^C \end{pmatrix} = \begin{pmatrix} 1 & \beta & 0 \\ 0 & \varphi_1 & \varphi_2 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} C_{t-1}^N \\ C_{t-1}^C \\ C_{t-2}^C \end{pmatrix} + \begin{pmatrix} \varepsilon_t^N \\ \varepsilon_t^C \\ 0 \end{pmatrix} \tag{6}$$

$$\Omega = \begin{pmatrix} \sigma_N^2 & 0 & 0 \\ 0 & \sigma_C^2 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{7}$$

To summarize, hysteresis is inferred if the coefficient β is significantly different from zero. The coefficients of the model (4)–(7) are estimated by maximum likelihood using a Kalman filter.

A non-linear version of this model (5)–(7) can also be estimated, to take account of the possibility that coal consumption displays asymmetries in adjustment dynamics in response to positive and negative shocks. Relaxing the linearity assumption may allow a better estimation of hysteresis if it exists. When we talk about "positive" or "negative" shocks, we do so relative to some threshold level, τ (where τ is not necessarily zero). To explore whether asymmetries exist, we estimate a non-linear version of the unobserved components model by allowing past cyclical consumption to have a different impact on the natural consumption, which depends on

[2] The assumption of a purely autoregressive process for the cyclical equation can be relaxed in favor of more general (and possibly more parsimonious) autoregressive moving-average specifications. In the present application, an AR(2) fits the data best according to AIC comparisons. Full results are available from the authors on request.

[3] However, as Proietti [14] states, this model is identified without this additional equation.

the regime of the economy. Specifically, we replace the state-space equation (6) with the Threshold Auto Regressive (TAR) specification

$$\begin{pmatrix} C_t^N \\ C_t^C \\ C_{t-1}^C \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \varphi_1 & \varphi_2 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} C_{t-1}^N \\ C_{t-1}^C \\ C_{t-2}^C \end{pmatrix} + \begin{pmatrix} \beta^+ \\ 0 \\ 0 \end{pmatrix} I_t^+ C_{t-1}^C + \begin{pmatrix} \beta^- \\ 0 \\ 0 \end{pmatrix} I_t^- C_{t-1}^C + \begin{pmatrix} \varepsilon_t^N \\ \varepsilon_t^C \\ 0 \end{pmatrix} \quad (8)$$

where I_t^+ and I_t^- are the Heaviside indicator functions such that:

$$I_t^+ = \begin{cases} 1 & \text{if} \quad C_{t-1}^C \geq \tau \\ 0 & \text{if} \quad C_{t-1}^C < \tau \end{cases}$$
$$I_t^- = \begin{cases} 1 & \text{if} \quad C_{t-1}^C < \tau \\ 0 & \text{if} \quad C_{t-1}^C \geq \tau \end{cases}$$

This model can be estimated via maximum likelihood using the Kalman filter, where τ is unknown so that it is estimated along with the other parameters of the model β^+ and β^-. In this context a test for asymmetry becomes a test for linearity, i.e. a test for a single regime against the alternative of two regimes. The null hypothesis we are interested in is $H_0 : \beta^+ = \beta^-$ vs. $H_0 : \beta^+ \neq \beta^-$. If we reject the null of linearity, there is evidence for the presence of a type of nonlinear hysteresis in coal consumption, i.e. with cyclical shocks being propagated asymmetrically to the natural component. Given our model, the asymptotic distribution of conventional test statistics is not χ^2.[4] To circumvent this problem we follow [13] who suggest using bootstrap methods to approximate the sampling distribution of the test statistic.

3. Results

This section presents the results in several stages. First, we test what Jaeger and Parkinson [2,3] have characterized as a necessary but not sufficient condition for hysteresis, namely the existence of a unit root in the coal consumption time-series. Second, we estimate the linear unobserved components model outlined in Section 2.2, incorporating a unit root as a maintained hypothesis. The third subsection explores the possibility of asymmetric behavior in adjustment dynamics, by estimating the nonlinear TAR unobserved components model, using the estimation strategy proposed by Pérez-Alonso and Di Sanzo [13].

3.1. Unit root tests

In order to test the hypothesis of non-stationarity, we apply the traditional Augmented Dickey–Fuller (ADF) test and a modified version of the Dickey–Fuller and Phillips–Perron tests proposed by Ng–Perron [17]. This comprises a class of modified tests, $\bar{M}$, with GLS de-trending of the data and use of the modified Akaike information Criteria to select the autoregressive truncation lag. Table 1 reports the results of Ng–Perron tests, $\bar{M}Z_\alpha^{GLS}$ and $\bar{M}Z_t^{GLS}$, originally developed in Stock [18] with GLS de-trending of the data as proposed by Elliot et al. [19]. In addition, Ng–Perron proposed a similar procedure that corrects the problem associated with the standard Augmented Dickey Fuller test, $\bar{M}SB^{GLS}$ and $\bar{M}PT^{GLS}$. All test statistics formally examine the unit root null hypothesis against the alternative of stationarity.

The results in Table 1 show that the null hypothesis of non-stationarity cannot be rejected, regardless of the test. However, it is well known that structural breaks in time-series can lead to spurious inferences of a unit root. To deal with this possibility, we employ the Zivot and Andrews [20] minimum *ADF-t*(*min-t*) procedure. The *min-t* statistics reported in Table 2 show that the null hypothesis of a unit root in the time series still cannot be rejected. This buttresses our conclusion that a unit root exists in coal consumption. As noted above, a unit root is a maintained assumption needed to test for Jaeger and Parkinson's notion of hysteresis. We investigate the notion of hysteresis next.

[4] See, e.g. Hansen [15] and Lo and Zivot [16].

Table 1
Unit root tests.

Variable	Coal consumption
$\bar{M}Z_\alpha^{GLS}$	0.492
$\bar{M}Z_t^{GLS}$	0.519
$\bar{M}SB^{GLS}$	1.056
$\bar{M}PT^{GLS}$	69.198
Lag length	11
ADF	−2.588***
Lag length	11
Range	1973:1–2010:3

Critical values (%)	$\bar{M}Z_\alpha^{GLS}$	$\bar{M}Z_t^{GLS}$	$\bar{M}SB^{GLS}$	$\bar{M}PT^{GLS}$
1	−13.800	−2.580	0.174	1.780
5	−8.100	−1.980	0.233	3.170
10	−5.700	−1.620	0.275	4.450

Critical values (%)	ADF
1	−3.476
5	−2.881
10	−2.577

Notes: Test statistics defined in the text. "Lag length" refers to the lag length used in the Ng–Perron and ADF tests, respectively. The critical values are tabulated in Ng and Perron [17].
*Rejects null hypothesis at 10% significance level.
**Rejects null hypothesis at 5% significance level.
*** Rejects null hypothesis at 1% significance level.

Table 2
Unit root tests allowing for structural breaks.

Variable		Coal consumption
A	*Min-t*	−0.807 (1983:3)
	Lag length	12
B	*Min-t*	−1.642 (2005:1)
	Lag length	12
C	*Min-t*	−1.571 (2000:2)
	Lag length	12
Range		1973:1–2010:3

Notes: Periods corresponding to *min-t* statistics are indicated in parentheses. Critical values for the *min-t* are given by Zivot and Andrews [20]. Asterisks are as in Table 1. *Min t*-statistics are computed using sequential regressions over 1 < trend break < *T* based on the following equations:

$$\Delta x_t = \delta_0^A + \delta_1^A t + \delta_2^A DU + \alpha^A x_{t-1} + \sum_{j=1}^{k} \phi_j^A \Delta x_{t-j} + e_t \quad (A)$$

$$\Delta x_t = \delta_0^B + \delta_1^B t + \delta_2^B DT + \alpha^B x_{t-1} + \sum_{j=1}^{k} \phi_j^B \Delta x_{t-j} + e_t \quad (B)$$

$$\Delta x_t = \delta_0^C + \delta_1^C t + \delta_2^C DU + \delta_3^C DT + \alpha^C x_{t-1} + \sum_{j=1}^{k} \phi_j^C \Delta x_{t-j} + e_t \quad (C)$$

where the dummy variables $DU_t = 1$ and $DT_t = t - TB$ for $t > TB$ and *0* otherwise, and *TB* denotes the period at which a possible trend break occurs. Critical values for the *min-t* are given by Zivot and Andrews [20]. In model (A): 1% (−5.34) 5% (−4.80) 10% (−4.58); model (B): 1% (−4.93) 5% (−4.42) 10% (−4.11); model (C): 1% (−5.57) 5% (−5.08) 10% (−4.82).

Table 3
Estimates of the linear unobserved component model.

Natural rate equation	
β	0.000 (0.014)
σ_N	0.021*** (0.003)
Cyclical rate equation	
ϕ_1	0.488* (0.291)
ϕ_2	−0.059 (0.071)
σ_C	0.015*** (0.004)
Identification equation	
α	0.654*** (0.090)
δ	−12.466* (6.471)
σ_D	0.773*** (0.092)
Range	1973:1–2010:3

Notes: Standard errors are in parentheses.
* Rejects null hypothesis at 10% significance level.
**Rejects null hypothesis at 5% significance level.
*** Rejects null hypothesis at 1% significance level.

Table 4
Non-linear model estimation results.

Natural rate equation		
β	1.076*** (0.123)	2.028*** (0.679)
σ_N	0.029*** (0.003)	
Cyclical rate equation		
ϕ_1	0.269** (0.130)	
ϕ_2	0.407*** (0.104)	
σ_C	0.010** (0.004)	
Identification equation		
α	0.300* (0.159)	
δ	7.185*** (2.206)	
σ_D	0.479** (0.211)	
Threshold	0.0137	
Delay lag	3	
% obs.	56.8	73.2
Range	1973:1–2010:3	

Notes: Standard errors are in parentheses.
* Rejects null hypothesis at 10% significance level.
** Rejects null hypothesis at 5% significance level.
*** Rejects null hypothesis at 1% significance level.

3.2. The linear unobserved component model

Table 3 presents the results of estimating (5)–(7) for coal consumption. The parameter β is zero and not statistically significant. However, should be rejected the existence of hysteresis in coal consumption? A likely reason of this rejection could be the presence of nonlinearity, and we should check it.

3.3. Asymmetries

We next check whether our results are robust to the linear specification of the unobserved component model.[5] This involves jointly estimating the structure (4), (6) and (7) to determine whether there is a threshold for cyclical consumption which is associated with asymmetric hysteresis responses. We wish to check whether the findings in the previous subsection are robust to possible asymmetries, or whether they were merely an artifact of the restrictive technical assumption of linearity.

The p-values calculated following the bootstrap technique described in detail in Pérez-Alonso and Di Sanzo [13]. The null hypothesis $H_0 : \beta^+ = \beta^-$ is rejected. Then, the hysteresis effect is significant at the 1% level.

In Table 4, we report the ML estimates of the hysteresis parameters. The threshold parameter is $\tau = 0.0137$. Hence, the threshold model splits the regression into two regimes depending on whether or not the threshold variable is higher than this threshold parameter. In both regimes, the hysteresis parameter is statistically significant and positive and the one associated with Regime 2 is greater than that of Regime 1. This result points to asymmetric responses of the natural component as regards cyclical consumption. Therefore, energy conservation policies might be more powerful than has been thought before. That is because any decrease in coal consumption brought about these policies will be incorporated into all future levels of consumption.

4. Conclusions

This paper estimated unobserved components models for coal consumption in the United States. Defining hysteresis in terms of the interdependent evolution of a non-stationary natural component and a stationary cyclical component, thereby distinguishing hysteresis from natural component shocks, the results provide robust evidence of hysteresis, although the hysteresis' coefficient is time varying. This implies that policy shocks in have permanent effects on coal consumption, although with different intensity depending on the regime. Future work might fruitfully apply the methodology used in this article to a broader range of energy sources and revisiting the robustness of some previous studies on energy consumption.

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